REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
	New Reprint	-

4. TITLE AND SUBTITLE
Cross-modal congruency benefits for combined tactile and visual signaling

5a. CONTRACT NUMBER
W911NF-08-1-0196

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
James L. Merlo , Aaron R. Duley, Peter A. Hancock

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Central Florida
Off of Res & Commercialization
12201 Research Parkway, Suite 501
Orlando, FL 32826 -3246

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
54182-LS.9

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
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15. SUBJECT TERMS
visual signaling, tactile signaling, cross-modal signaling

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Peter Hancock
					19b. TELEPHONE NUMBER
					407-823-2310

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Cross-modal congruency benefits for combined tactile and visual signaling

ABSTRACT

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REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Continuation for Block 13

ARO Report Number 54182.9-LS
Cross-modal congruency benefits for combined ...

Block 13: Supplementary Note

Cross-modal congruency benefits for combined tactile and visual signaling

JAMES L. MERLO
United States Military Academy, West Point

AARON R. DULEY
NASA Ames Research Center

PETER A. HANCOCK
University of Central Florida, Orlando

This series of experiments tested the assimilation and efficacy of tactile messages that were created based on five common military arm and hand signals. We compared the response times and accuracy rates for these tactile representations against responses to equivalent visual representations of the same messages. Experimentally, such messages were displayed in either tactile or visual forms alone, or using both modalities in combination. There was a performance benefit for concurrent message presentations, which showed superior response times and improved accuracy rates when compared with individual presentations in either modality alone. Such improvement was due largely to a reduction in premotor response time. These improvements occurred equally in military and nonmilitary samples. Potential reasons for this multimodal facilitation are discussed. On a practical level, these results confirm the utility of tactile messaging to augment visual messaging, especially in challenging and stressful environments where visual messaging is not feasible or effective.

Humans rely on their multiple sensory systems to continuously integrate the environmental stimuli around them. This integration allows them to build their perception of the world in which they live. Although each sense alone is remarkably adept at detection, it is the combination and integration of these disparate sensory inputs that provide the rich tapestry of spatial, temporal, and object-related information on which humans rely to survive and thrive. Cross-modal fusion of these information sources often proves more beneficial than simply increasing information from only one sensory modality. For example, Hillis, Ernst, Banks, and Landy (2002) found that when combined, the value of multiple visual cues (e.g., disparity and texture gradients) did not produce as accurate performance as when both visual and tactile cues were provided in an object property discrimination task. Comparing performance within the same modality with combinations of two or more different modalities illustrates that information loss can occur during intramodal presentations that does not occur with the fusion across different modalities. In the specific case of tactile and visual information there seems to be a highly efficient integration of the two sources (Ernst & Banks, 2002). This integration is especially beneficial when the cross-modal cues

American Journal of Psychology
Winter 2010, Vol. 123, No. 4 pp. 413–424 •

are congruent and match the top-down expectancies generated by past experience.

Previous research on cross-modal effects has overwhelmingly used simple forms of stimulation in experimentation. For example, such stimuli are composed of the illumination of a simple light display; tactile signals are represented by one single point stimulation. Much may be learned about the basic psychophysics of cross-modal effects through these laboratory-based forms of signal. However, real-world patterns of stimulation are often complex and convey important meaning beyond recognition of a simple sensory change. Unfortunately, very little is known about cross-modal integration effects when the presented stimuli are complex. Extrapolation from the basic understanding of the fundamental psychophysics to the actual presentation of real-world signals is neither as pristine nor as linear as is often expected. Rich, meaningful, and information-laden signals are not always treated as linear assemblies of simple signals. Thus, although the findings from extant basic research establishing cross-modal advantages (e.g., Spence, Pavani, & Driver, 2004) are important, such advantages have yet to be fully established in relation to real-world performance tasks. Therefore, the primary purpose of the present work was to examine such cross-modal congruency effects in circumstances using direct, meaningful, real-world signals. In these more applied settings, if the cross-modal advantage of the integration of visual and tactile information is confirmed, it could improve on single-modality communication. Such an advantage would be especially evident when any particular sense is overloaded or otherwise degraded by some local masking conditions. For example, in extreme operational conditions, such as military combat or firefighting, the capacity to create and retain some form of redundancy gain is not merely useful, it may even prove critical to survival (Hancock & Szalma, 2008). This pursuit of increased communication capacities is important because missed or misinterpreted signals or messages in such situations can have catastrophic consequences (Reason, 2008).

Humans not only rely on their multiple sensory capacities to integrate different forms of stimuli, they also use these multiple sources to aid them in the initial process of orientation and the subsequent focus of their attention in space and time. When a person directs her or his attention toward a particular location, regardless of the primary modality used in the process of detection, the other modalities are often directed toward that same location. Indeed, there is an ongoing debate about whether the orientation of attention is a multisensory construction (Spence & Driver, 2004) or an overdominantly visual process (Posner, Nissen, & Klein, 1976). This issue can be approached from a neurophysiological perspective. For example, Stein and Meredith (1993) showed that bimodal and trimodal neurons have a stronger cellular response when animals are presented with stimuli from two sensory modalities as compared with stimulation from only one modality. The combinations of two different sensory stimuli significantly enhance the responses of neurons in the superior colliculus compared with those evoked by either unimodal stimulus alone. This observation supports the conclusion that there is a multisensory link between individual superior colliculus neurons for cross-modality attention and orientation behaviors (see also Meredith & Stein, 1996; Wallace, Meredith, & Stein, 1998).

Recent findings also reinforce the proposition that multisensory processing is possible for unimodal neurons. Allman and Meredith (2007) used cellular recordings to measure responses of neurons in the postlateral lateral suprasylvian of the cat. Although unimodal visual neurons did not respond when presented only auditory stimuli, they did have an enhanced visual response with concurrently presented auditory stimuli. This finding indicates that bimodal and trimodal neurons are not the exclusive domain for multimodal processing. It suggests that potentially, there is a subthreshold multisensory neuron that contributes to the processing of multimodal stimulation. This may be a basis for the finding that behavioral responses to bimodal stimuli are faster and more accurate than for unimodal stimuli (Teder-Salejarvi, Di Russo, McDonald, & Hillyard, 2005). Problematically, multimodal stimulation in the real world is not always presented or received in a congruent spatial and temporal manner. This ambiguity can be resolved by overreliance on the one single dominant system, which in humans is expressed in the visual modality (Hancock, 2005). However, when there is a strong expectation from past experience that real-world multisensory information will be congruent

and consistent, but it proves not to be so, the result is often perceptual error.

As we have noted, to date the exploration of cross-modal attention has relied mainly on simple stimuli to elicit responses (Spence & Walton, 2005). As a specific example, Gray and Tan (2002) used a number of tactors (vibrotactile actuators) spanning the length of the participant's arm with lights mounted on the individual tactors. Using an appropriate interstimulus interval and tactor spacing (see Geldard, 1982; Geldard & Sherrick, 1972; Helson & King, 1931), Gray and Tan created the illusion of movement, either up or down the arm. These researchers found that response times were shorter when the visual target was offset in the same direction as the tactile motion (similar to the predictive abilities one has to know the location of an insect when it runs up or down the arm). Reaction times were longer when the target was offset in the direction opposite to the tactile motion. This further supports the contention that the cross-modal links between vision and touch are updated dynamically for moving objects and are best supported perceptually when the stimuli are congruent. However, it also illustrates again that extant work has used only very simple patterns of stimulation.

In another such study, Craig (2006) had participants judge the direction of apparent motion by stimulating two locations sequentially on a participant's finger pad using vibrotactors. Visual trials included apparent motion induced by the activation of two lights sequentially. Some trials were recorded with both visual and tactile stimuli presented together either congruently or incongruently. When visual motion was presented at the same time as but in a direction opposite to tactile motion, accuracy in judging the direction of tactile apparent motion was substantially lower. This superior performance during congruent presentation was called the congruency effect. Strybel and Vatakis (2004), who used visual apparent motion, conducted a similar experiment. They found similar effects for judgments of auditory apparent motion. Auditory stimuli have also been shown to affect the perceived direction of tactile apparent motion (see Soto-Faraco, Spence, & Kingstone, 2004a, 2004b).

Bensmaia, Killebrew, and Craig (2006) had participants make discrimination judgments comparing pairs of tactile stimuli with drifting sinusoids. On some of the trials a visual drifting sinusoid was presented simultaneously with one of the two tactile stimuli. The visual stimuli served as a distraction that was to be ignored. When the directions of drift for the visual and tactile grating displays were congruent, the presence of the visual distractor increased the perceived speed of the tactile grating. When the two stimuli were incongruent (i.e., they drifted in opposite directions), the effect of the visual distractor was to reduce the perceived speed of the tactile grating. Although all these experiments with simple tasks are essential for understanding the psychological phenomena under consideration, the extension of these findings into real-world conditions to embrace more applied stimuli is essentially unexplored. However, with advancements in tactile display technology and innovative signaling techniques, the importance of evaluating the occurrence and power of these multimodal enhancements in systems capable of assisting actual field communications is now both feasible and pragmatically important. Thus, the goal of the present sequence of experiments was to examine combinations of visual and tactile communications of real-world operational signals in order to evaluate whether the pattern of findings from simple forms of stimulation persisted in real-world circumstances. We also evaluated whether the presentation of inconsistent multimodal information caused any significant change in response capacity using these real-world signals.

EXPERIMENT 1

METHOD

Participants

To investigate the effectiveness of cross-modal information presentation of complex, real-world complex signals, 20 participants (9 men, 11 women) ranging in age from 18 to 48, with an average age of 25 years, volunteered to participate in the first experiment. Each participant self-reported no surgeries, significant scarring, or any impediment that might cause lack of feeling in the abdomen or torso area where the tactile signals were presented. Furthermore, all participants reported normal or corrected-to-normal vision. Additionally, none of the participants had any prior experience with either the visual arm and hand signals or the specific form of tactile signaling used in the experiment.

Materials and apparatus

The vibrotactile actuators (tactors) used in the present system were model C2, manufactured by Engineering Acoustics, Inc. They were acoustic transducers that displace 200- to 300-Hz sinusoidal vibrations onto the skin. Their 17-g mass was sufficient for activating the skin's tactile receptors. The C2's contactor was 7 mm, with a 1-mm gap separating it from the tactor aluminum housing. The C2 is a tuned device, meaning that it operates effectively only within a very small frequency range. In the present experiment, this operational range was centered on 250 Hz. The tactile display itself was a belt-like device with eight vibrotactile actuators embedded in it. Three examples of the present belt system are shown in Figure 1. The belt itself was made of elastic material and was composed of high-quality cloth similar to that used by professional cyclists. When the belt is stretched around the body and fastened, one actuator is centered over the umbilicus and one is centered over the spine. The other six actuators are equally spaced around the body, three on each side, for a total of eight (see also Cholewiak, Brill, & Schwab, 2004).

The tactors are activated using a tactor control unit. This is a computer-controlled driver and amplifier system that switches each tactor on and off as commanded by the associated software. Controller devices are also shown on the left side of the belts in Figure 1. The control unit weighs 1.2 lb independent of its power source and is approximately 1 inch thick. This device connects to a power source with one cable and to the display belt with the other. It uses Bluetooth technology to communicate with the computer-driven interface. We created tactile messages based on five standard Army and Marine Corps arm and hand signals (Department of the Army, 1987). The five signals chosen for the present experiment were "Attention," "Halt," "Rally," "Move Out," and "Nuclear Biological Chemical Event (NBC)." The specific tactile representations of these signals were designed in a collaborative effort involving a consultant group of subject matter experts including former U.S. soldiers and Marines.

We created five short video clips of a soldier in uniform performing these five arm and hand signals. These video clips were the visual stimuli for the study. Careful editing ensured that the timing of the arm and hand signals matched the temporal duration and patterning of the tactile presentations (Figure 2). We used a Samsung Q1 Ultra Mobile computer using an Intel Celeron M ULV (900 MHz) processor with a 7″ WVGA (800 × 480) liquid crystal display to present videos of the soldier performing the arm and hand signals. This computer ran a custom LabVIEW (8.2; National Instruments) application that presented the comparable tactile signals via Bluetooth to the tactor controller board. The computer also captured all participant responses via mouse input. Participants wore sound-dampening headphones with a reduc-

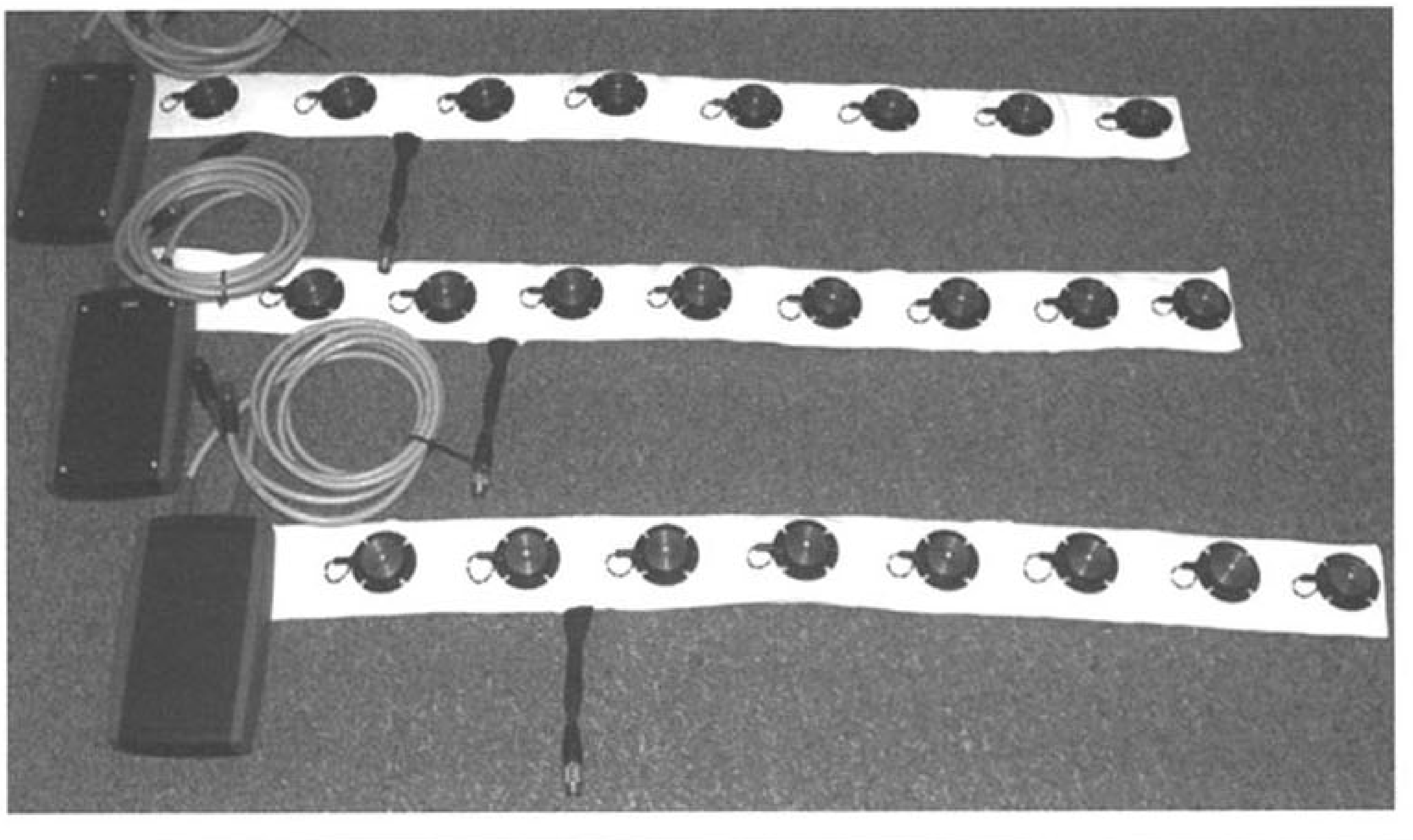

FIGURE 1. Three tactile display belt assemblies and their associated controller boxes

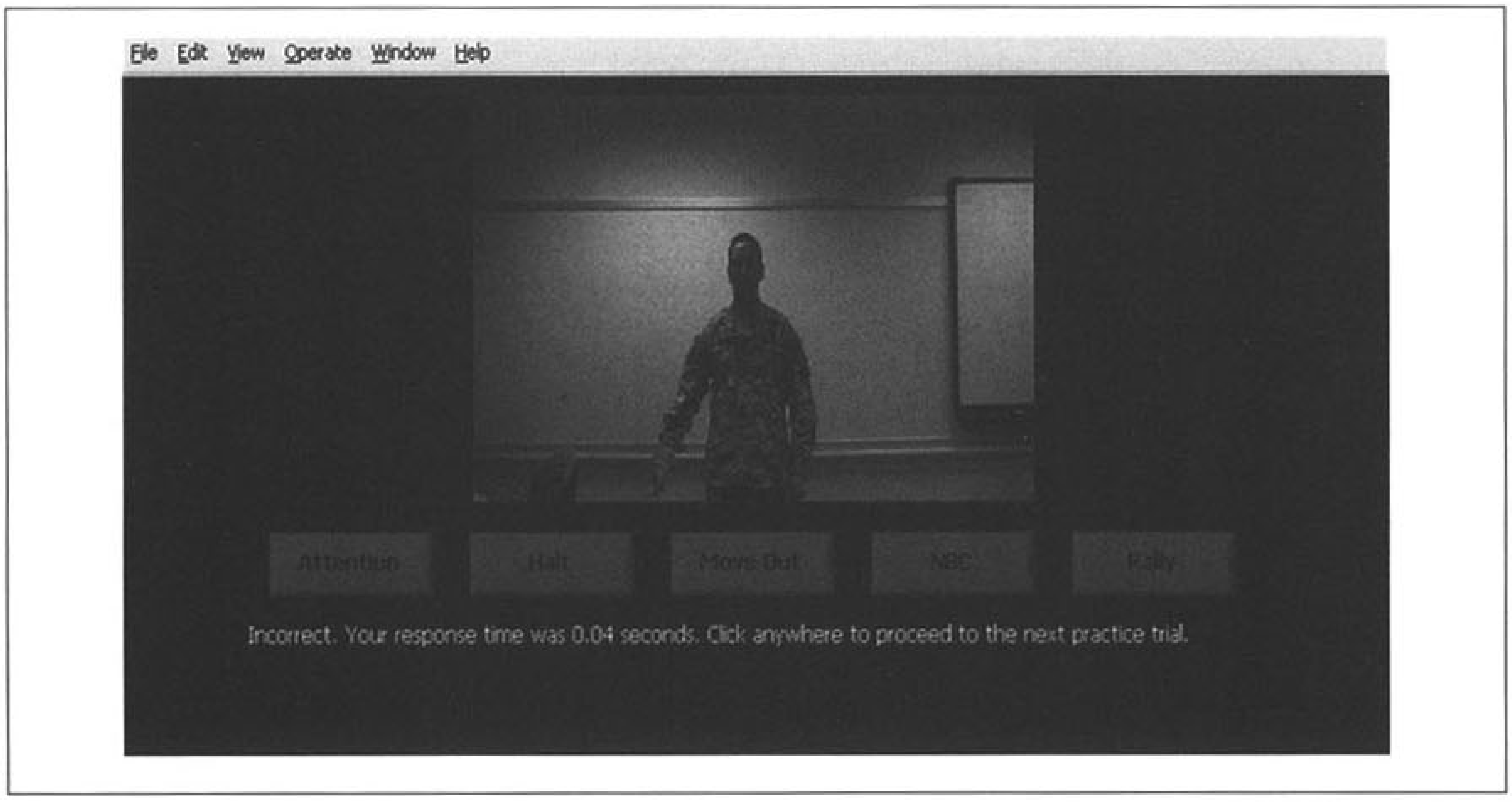

FIGURE 2. Screen shot showing what the participant viewed as the signals were presented. The participant mouse-clicked on the appropriate signal name after each presentation

tion rating of 11.3 dB at 250 Hz. This precaution was designed to mask any possible effects of extraneous auditory stimuli produced by tactor actuation. Because this issue has caused controversy, we were careful to control for this potential artifact here (cf. Broadbent, 1978; Poulton, 1977).

Each message or signal was displayed in one of four distinct ways. First was the visual-only condition. This consisted of the five arm and hand signals shown on video. Second, the tactile-only presentation communicated the five tactile equivalents of the arm and hand signals. Third, in the congruent-both condition the visual form and the tactile form of the same signal were presented simultaneously. Finally, in the incongruent-both condition visual and tactile signals were presented simultaneously, but the visual version did not match the tactile version of the signal.

Design and procedure

Participants first viewed a computer-based tutorial that described each arm and hand signal individually. For each signal, a short description of the action was presented. Participants then viewed a video of a soldier in uniform performing the signal, followed by a direct experience of its tactile equivalent. Finally, the participants were able to experience the signals concurrently (both visual and tactile congruent representations together). Participants were allowed to repeat this presentation (i.e., visual only, tactile only, and congruent both) as many times as they desired.

Once the participant had completed this experience, a validation exercise was performed. In this exercise, participants had to correctly identify each signal twice before the computer would prompt the experimenter that the participant was ready to begin the formal experimental procedure.

Each participant performed two 60-trial blocks. Each block had two trials of each signal presented in the visual-only condition (10 total trials), two of each signal presented in the tactile-only condition (10 total trials), four of each signal in the congruent-both condition (20 total trials), and four of each in the incongruent-both condition (20 total trials). These 60 summed trials composed one block. Each participant performed two such blocks. Within blocks, trials were randomized for each participant. The entire experiment took just less than an hour to complete.

RESULTS

All reported analyses were conducted using an alpha level set at .05. Results were analyzed in terms of the speed of the response and the accuracy of the response under the respective performance conditions. Because the incongruent-both condition raised a number of issues in analysis, the initial comparisons are derived from the visual-only, tactile-only, and congruent-both conditions only. An analysis of variance (ANOVA) was performed on the mean response times across the three described experimental conditions,

$F(2, 57) = 2.85, p < .05, (\eta^2_p = .130, \beta = 0.653)$. Subsequent pairwise analysis indicated that the simultaneously presented congruent-both signals resulted in significantly shorter response times than visual-only signals, $t(19) = -2.25, p < .04$. Analysis also indicated that congruent-both signals were faster than those for tactile-only, $t(19) = -3.98, p < .01$. Finally, the visual-only presentation was significantly faster than the tactile-only presentation, $t(19) = -2.16, p < .04$. These findings are illustrated in Figure 3.

With respect to response accuracy, a marginal difference was observed between the visual-only and tactile-only signals. However, this just failed to reach the preset level of significance, $t(19) = 2.00, p < .06$. However, there was a significant difference in accuracy when the tactile-only was compared with the congruent-both presentation of the signals, $t(19) = 4.03, p < .01$. The lower accuracy rate for the tactile-only appears to be due to confusion between the tactile signal for "NBC" and "Halt," which have very similar tactile characteristics, although they have a very low level of similarity in the visual presentations. When the data for the "NBC" tactile signal were removed, though, the results did not show even the marginal difference in error rate between visual-only and tactile-only signals. However, such removal did not affect the significant main effect between the tactile and the congruent-both condition. After this initial comparison between visual-only, tactile-only, and congruent-both conditions had been conducted, we examined comparisons including the incongruent-both condition.

Results for the incongruent-both condition were analyzed in terms of the speed and accuracy of the response. During incongruent-both trials, the participants chose their preference for tactile or visual presentation (where no specific instructions were given to the participants on how to deal with this conflict of signals). In some cases, neither of the presented signals was selected by the participants, therefore the response was coded as a "response not matching either presentation," with 9 out of 20 participants making this type of error at least once. Participants' selections were examined during incongruent-both trials to determine which signal modality they responded to most frequently. There was an overall preference for choosing the visual presentation over the conflicting tactile signal. The mean response time for the incongruent-both trials is also shown in Figure 3.

Although not significantly slower than visual-only presentations, $t(19) = -0.150, p < .88$, or tactile-only presentations, $t(19) = 1.43, p < .17$, incongruent-only presentations were significantly slower than congruent-only presentations, $t(19) = -3.778, p < .01$. The responses that did not correspond with either modality of the presented signal were not considered in this comparison. This meant that 36 out of 800 trials were omitted from that analysis and analyzed separately. The mean response times of these trials were computed, and Figure 3 shows that longer response times were associated with these respective responses that did not match either of the incongruent modality presentations. Participants reported confusion on not being told which modality took precedence. Most participants stated that they would pick one modality in order to try to be consistent. However, others reported that they would still often choose the other modality. Thus, responses not matching either presentation apparently caused a longer than nor-

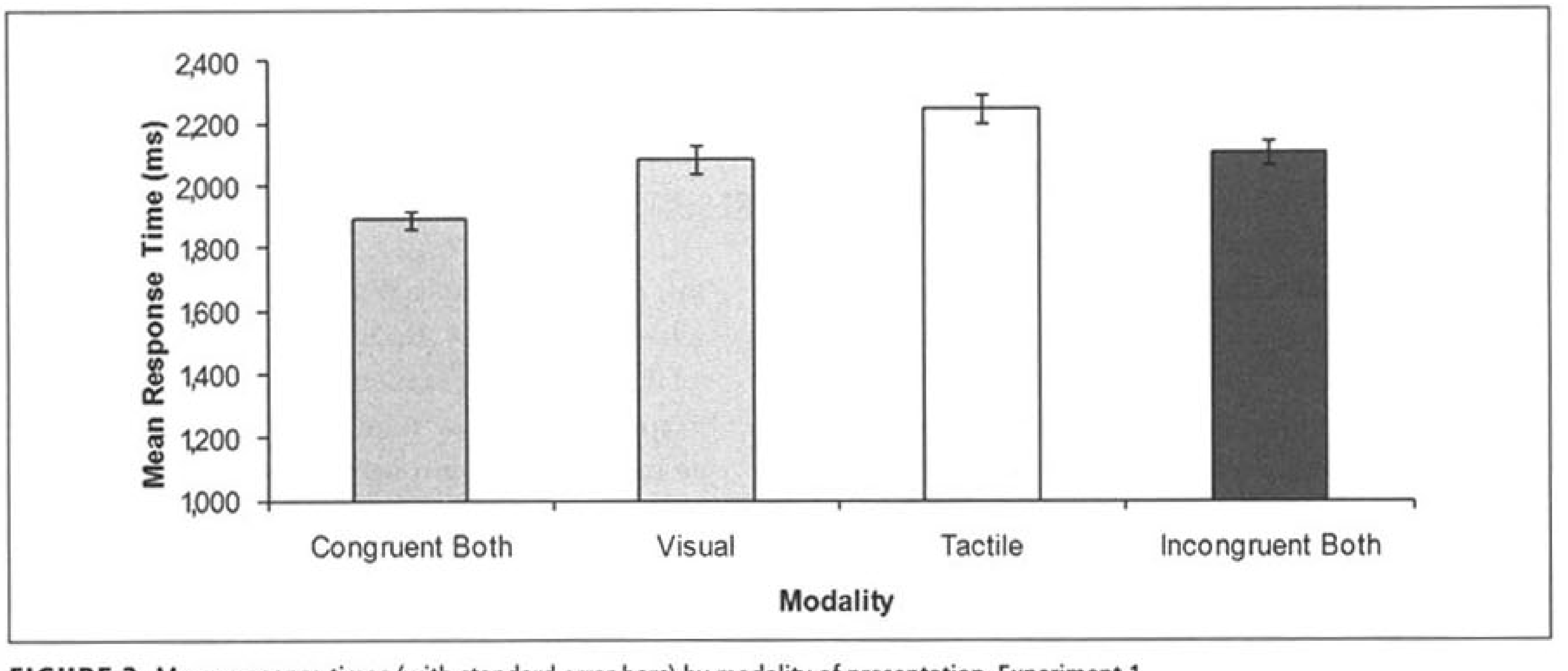

FIGURE 3. Mean response times (with standard error bars) by modality of presentation, Experiment 1

mal decision-making process, as represented by the longer and more variable response times here. The introduction of the incongruent-both form of presentation proved disconcerting for most participants. The majority of participants asked for clarification when the first or second incongruent-both trial was presented during the randomized sequence. In an effort to support experimental fidelity, this questioning by the participant was answered with a repeat of the instructions that they were to follow.

The overall high accuracy rate. which was represented by a response accuracy of more than 80% in all modalities with fewer than 10 min of total training, is highly encouraging to the current form of tactile display for real-world applications. The accuracy of the messages and the reported intuitiveness with which they were received confirmed the utility of the presently selected forms of tactile message. Similarities between various tactile-only and visual-only signals, which caused potential confusion between signals when presented in one modality alone, was essentially eliminated in concurrent-both presentations. The confusion and subsequent errors created in comparisons of the tactile-only signals might have been exacerbated by the presence of interpolated incongruent-both trials (i.e., the trials in which tactile and visual signal did not match). Overall, the present data confirm an advantage for multimodal signal presentation. It was also demonstrated that this advantage was not due to any trade-off of speed for accuracy. The next logical question was to ascertain the source of this specific processing advantage. This was the subject of the next experiment.

EXPERIMENT 2

METHOD

Participants

Seventy-two participants (47 men, 25 women) ranging in age from 18 to 21, with an average age of 18.5 years, volunteered to participate. Of these, 31 were from the University of Central Florida, and the remaining 41 were from the U.S. Military Academy. The primary difference between the samples was that the latter group had prior experience with the visual form of the presented arm and hand signals. However, the tactile form of the signals was new to all participants. As in Experiment 1, each participant had no impediment that could cause lack of feeling in the abdomen or torso area and no visual impairments that would obscure their capacity to respond to the visual signals.

Materials, apparatus, design, and procedure

All experimental materials and apparatus were the same as those described in Experiment 1. The experimental design and procedures for this experiment were similar to those of the first experiment, with a small number of important differences. First, all incongruent-both trials were removed from the procedure. Therefore, each signal was presented in one of only three ways: the visual-only condition, in which the participant viewed the edited video presentation of the arm and hand signals; the tactile-only condition, which presented the comparable tactile versions of the arm and hand signals; and the congruent-both condition, in which both visual and tactile representations of the same arm and hand signal were presented.

Following the same sequence of orientation and practice session as described in Experiment 1, each participant completed the required performance trials. The participants were presented each of the five signals eight times each. They were presented under the three different conditions—visual only, tactile only, and congruent both—for a grand total of 120 trials. The order in which each participant performed the sequence of trials was completely randomized.

The primary difference in the present experiment was in the format of response. Before each trial began, the participant had to place the mouse cursor inside a small square in the center of the screen. The presentation of the signal, regardless of its modality, started the timer, and the following performance responses were collected: the initial movement of the mouse, the latency to name the received signal, the signal named, and the accuracy of that choice. This format permitted us to parse the response into premotor time (the first movement of the mouse) and motor time (the time to place the cursor in the response box) for both correct and incorrect responses. These responses were subjected to analysis.

RESULTS

Results were analyzed in terms of the speed of the response and the accuracy of the response under the respective conditions. We conducted an initial analysis to assess any potential sex differences across participants. However, no significant influence of this factor was found on any of the measures recorded,

therefore, the subsequent analysis was collapsed across the sexes. A one-way ANOVA was performed on the mean response times across the three experimental conditions of visual-only, tactile-only, and congruent-both presentations, $F(2, 213) = 9.37, p < .01, \eta^2_p = .961, \beta = 1.00$. Post hoc analysis showed that congruent-both signals resulted in a significantly shorter response time than the visual-only condition, $t(71) = 3.15, p < .01$. Responses to the congruent-both signals were also faster than tactile-only responses, $t(71) = 10.29, p < .01$. Additionally, the visual-only presentation of the signal was significantly faster than the tactile-only presentation, $t(71) = -4.15, p < .01$. These results are illustrated in Figure 4. The data were examined for effects of gender in the different modalities. A general linear model MANOVA of the within-subject variables of modality (visual, tactile, and congruent) and between-subject variable of gender (male and female) was conducted for response time means, $F(2, 36) = .642, p < .532, \eta^2_p = .034, \beta = .149$, but there was no significant difference between women and men in any of the modalities.

Analysis of the response accuracy data showed a significant difference in accuracy between the visual-only and tactile-only conditions, $t(71) = -7.10, p < .01$. This difference was probably due to the extraordinarily high accuracy level in the visual-only condition. This may be due in part to the military participants already being familiar with and having some previous training in the visual form of the signals. In contrast, none of the participants had any prior experience with the tactile form of the signals presented here. There was also a significant difference in the accuracy rate when responses to the tactile-only condition were compared with the congruent-both presentation, $t(71) = 7.47, p < .01$, with the congruent-both condition being more accurate. The overall lower accuracy rate for tactile-only signaling is again attributed to the confusion between the tactile signal for "NBC" and "Halt." Analysis without the "NBC" tactile-only signal data removed the reported significant differences in response accuracy. There was no significant difference between responses for the visual-only condition and the combined-both condition.

A one-way ANOVA was performed on the mean response times for the premotor element (the time that elapsed from presentation of the signal to the first movement of the mouse) across the three experimental conditions. This analysis showed a significant effect, $F(2, 213) = 5.48, p < .01, \eta^2_p = .961, \beta = 1.00$. Subsequent pairwise comparisons showed that simultaneously presented congruent-both signals resulted in a significantly shorter premotor response time than visual-only condition, $t(71) = 4.30, p < .01$. Congruent-both response times proved significantly shorter than the premotor times for the tactile-only condition, $t(71) = -2.9, p < .01$. Additionally, premotor response times for the visual-only presentation were signifi-

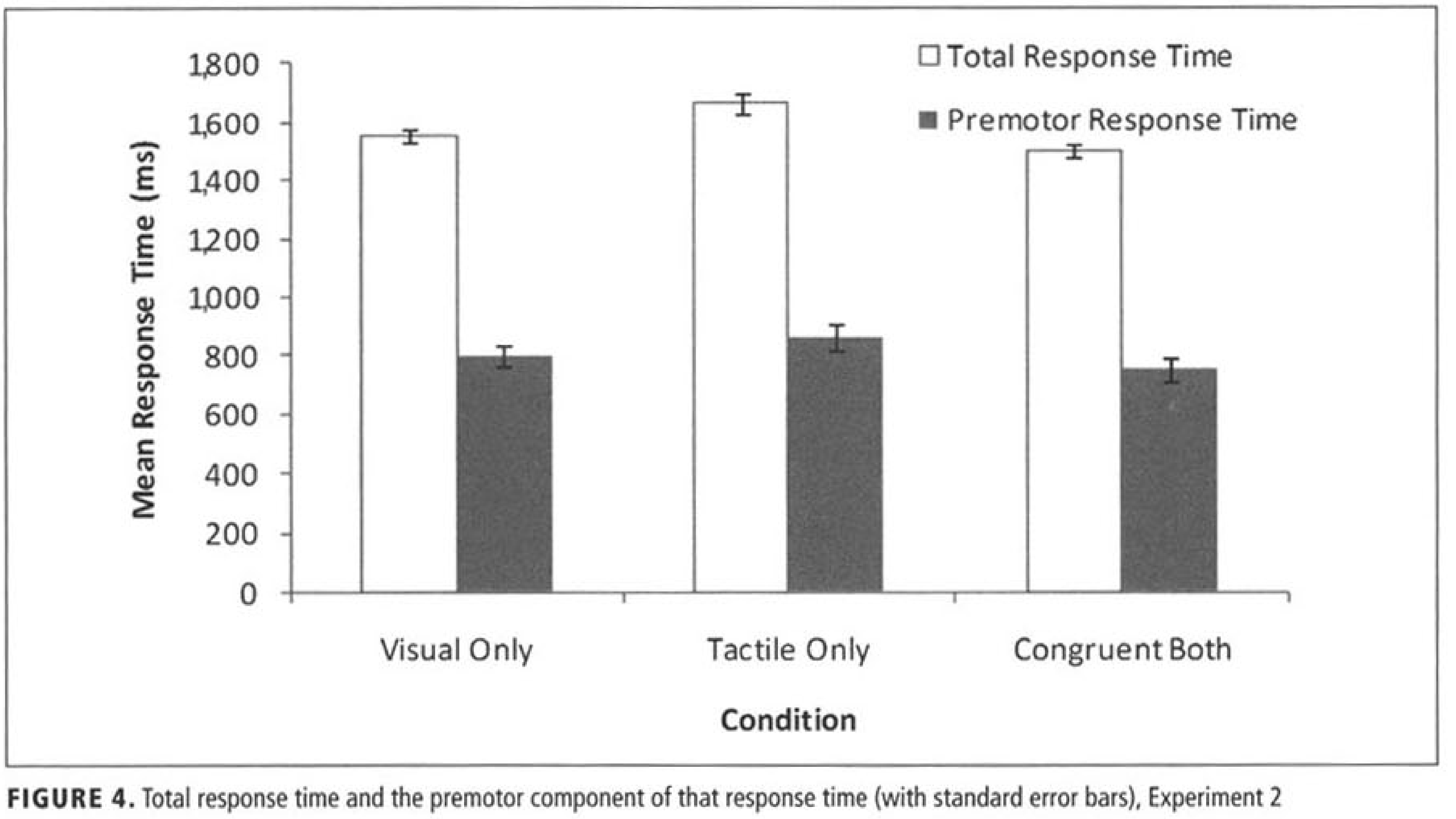

FIGURE 4. Total response time and the premotor component of that response time (with standard error bars), Experiment 2

cantly shorter than the premotor responses for the tactile-only presentation of the signal, $t(71) = -2.89$, $p < .01$. These results are also illustrated in Figure 4. In addition to the premotor response times, the present design permitted analysis of the motor response times themselves that represented the latency to move to the designated response location. No differences were found across any of the experimental conditions for motor response latency.

It was further hypothesized that there would be some differences between the two sample groups of students. In particular, this hypothesis derived from the understanding that because of their experience with the hand signals communicated, cadets may have greater facility in response. In contrast, the university students were encountering these signals for the first time. To a degree, any such initial difference ought to have been mitigated by the practice given. However, we chose to examine this hypothesis analytically. A t test did detect such a difference, which was evident in the premotor response time to the tactile-only signals alone, $t(70) = 1.99$, $p < .01$ (military cadets = 785 ms vs. university students = 956 ms).

DISCUSSION

The present results show a facilitation in processing speed when two consistent signals are presented together in both modalities. This outcome exemplifies the redundant signals effect (see Kinchla, 1974). Rather than a statistical advantage derived from the race between the activation of two separated streams of incoming information, the observed facilitation appears more likely to be due to a process of coactivation (Miller, 1982; also see Rach, Diederich, Steenken, & Colonius, 2010). This form of descriptive explanation is supported by more extensive understanding of the underlying neurophysiological processes (see Allman & Meredith, 2007). Facilitation might have derived from a change in response decision criterion, but the effect cannot be attributed to a trade-off of speed for accuracy because the consistent-both condition was significantly more accurate than the tactile-alone presentation and as accurate as the visual-alone presentation in the first experiment, and this pattern of results persisted in the second experiment. This result might have been affected by confusion between two specific forms of tactile signal. However, even if this were the case, the consistent-both condition shows responses that are at least as accurate as the visual-only and tactile-only conditions. The multimodal advantage is not the result of any trade-off of speed for accuracy. What emerges is a genuine advantage in performance for the multimodal condition. There are a number of potential reasons why this may occur. First, we can look to the methods of the first experiment, in which incongruent signals (i.e., the co-occurring visual and the tactile representations were those of different signals) were embedded in the design. However, the interpolation of the inconsistent signals should have had a deleterious effect on performance, not the enhancement we observed. If the interjection of inconsistent signals had an inhibiting effect, then the overall enhancement of consistent-both condition may be even greater than reported. At the present, we must affirm some form of multimodal advantage that derives from the facilitation due to cross-reinforcement of incoming sensory signals.

In the course of these experiments, we examined the responses of both men and women. However, analysis of both experiments indicated no gender differences. Because the tactile signals are largely spatial emulations of their visual counterpart, this outcome was not especially surprising. Gender differences found in spatial cognition tasks often are due to mental rotation differences, and little or no mental rotation seems to be needed for tactile signal comparison or interpretation (Voyer, Voyer, & Bryden, 1995). Additionally, some researchers have reported a decline in gender differences due to social and nurturing changes in today's more gender-neutral environment (Feingold, 1988). Furthermore, other factors such as athletic participation and specific skills development may mask or negate any such differences (Hancock, Kane, Scallen, & Albinson, 2002), and this may be especially true of the cadet sample in Experiment 2. However, it should be acknowledged that the sample size in the present experiments was small. Thus, more extended comparisons may be justified because demonstrated differences still exist for many spatial tasks (see Maccoby & Jacklin, 1974), and these trends are well substantiated in the literature (Masters & Sanders, 1993). In practical terms, though, the present outcome is encouraging because it suggests that both men and women will benefit equally from any

developed real-world technologies based on the multimodal advantage identified here.

To return to the issue of why this multimodal advantage is observed, a more realistic source for the enhancement may lie in the neurophysiologic architectural linkages discussed in the introduction to this article. It appears that cross-modal reinforcement has a direct effect on the strength of synaptic transmission that is experienced early in the stimulus processing sequence. Experiment 2 was conducted to explore this possibility. In that experiment, the response was parsed to isolate the motor output component of the response sequence. We found a strong confirmation of the multimodal presentation advantage for complex stimuli and of the isolation of that advantage into the early, premotor stages of response. At present, it is uncertain whether the primary advantage is to be found in the perceptual recognition phase of the information-processing sequence or in the decision-making and response formulation element of that sequence. However, the distinction of such a difference should be amenable to subsequent identification. From the present results it appears that a neurophysiological argument underlying cross-modal stimulation is the best candidate account for the early advantage offered by consistent multimodal signaling. Our findings further affirm that the multimodal advantage demonstrated with very simple stimuli does persist when the signals used are rich in information and meaning.

Our results have implications beyond the explanation of the physiological dimensions of multimodal sensory assimilation. First, there is a learning dimension of the present forms of signaling. Whereas the visual forms of the arm and hand signals have been developed and used by the military over an extended period, the tactile equivalents were developed here only for the purposes of the present study. Nevertheless, all participants learned these forms of tactile signals rapidly. There was more than 80% recognition of these signals with less than 10 min of training. This suggests that tactile signaling may be a highly effective form of communication even for complex signals. The promise of this facility is that a simple, low-baud-rate language of the skin may eventually be developed for wider human communication capacities. Such development may have important implications for various disabled populations.

The absence of any observed gender difference is encouraging for the subsequent field use of multimodal communication capacities. As we have noted, such signaling can thus be ubiquitously administered in applied operational conditions. The finding that military personnel performed better in the tactile element than in the visual form with which they were already familiar is an especially intriguing result. It could be argued that because of their familiarity with the visual signals, the military participants exerted a greater effort to learn the tactile signals and therefore were better able to respond to them. However, all participants had an equal opportunity to learn all the signals to a criterion level, a fact that militates against such an explanation. It could also be argued that this reflected a sampling bias because military cadets are already under a greater selection pressure when initially entering their institution. In essence, the cadets are simply better performers on an absolute level. However, if this were so such superiority would be expected to be reflected in all facets of performance. The present data do not support such a proposition. At present, there is no evident explanation for this observed difference, and it is possible that this is a spurious finding. However, the absolute performance difference was large and consistent and therefore is unlikely to be a chance result.

The question of learning complex tactile communication signals, especially for use in adverse or unusual circumstances, is an important future issue in both practical and theoretical realms. The tactile system can clearly act as a redundancy gain by giving participants multiple means of receiving communication. In practical terms, this backup line of communication might well assume preeminence, especially in highly adverse conditions (e.g., firefighting) when obstructions to vision and audition make other forms of communication impossible. It may also be a critical alternative avenue of information presentation under stress (Hancock & Warm, 1989). Although the current findings show superior performance for the recognition of tactile arm and hand signals in a multimodal form of presentation, many challenges to integrated multimodal signaling in the real world remain. Stimulus–response compatibility (see Proctor & Vu, this issue) will have to be assessed carefully to maximize performance as different types of

inputs are considered for use with combined visual and tactile displays. However, when people are faced with extreme challenges and traditional sources of visual or auditory information are diminished or degraded in some fashion, tactile stimulation provides an important augmented communication channel. The fact that complex, informationally rich messages can be facilitated by such multimodal presentation is itself evidence that important basic research findings can be extended and elaborated into crucial real-world application.

NOTES

Address correspondence about this article to J. L. Merlo, United States Military Academy, West Point, NY 10996 (e-mail: james.merlo@usma.edu).

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